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Magneto-resistance anisotropy and planar Hall effect in polycrystalline nickel and nickel copper alloys

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Measurements of planar Hall ot effect, longitudinal and transverse magneto-resistances are reported on polycrystalline Nickel and Nickel Copper alloys in the temperature interval 100°K to the respective Curie points. The magneto-resistance anisotropy and planar Hall resistivity are compared and the discrepancy in the values are attributed to the possibility of magnetization vector not lying in the plane of the sample Further, it is remarked that the spin-orbit interaction mechanism is the common cause of origin of planar Hall effect as well as magneto-resistance anisotropy. To explain the present experimental results, the scattering of conduction electrons by both the phonons and impurities are taken into account.

1 Introduction

Following Jan (1952), it may be shown that the electric field of a ferromagnetic plate specimen (with its plane along the xy plane) transverse to the current direction (x-direction) in the same plane is given by

$$E_y = n_x n_y(\rho_{\|s}-\rho_{\perp s})j+\rho_{Ts}n_z j \tag{1}$$

where j is the current density, n_x, n_y, n_z are the direction Cosines of magnetization along the three coordinate axes, $\rho_{\|s}$, $\rho_{\perp s}$ the saturation reistivities parallel and perpendicular to the magnetization direction and ρ_{Ts}, the Hall resistivity at saturation.

The second term in eq. (1) is the true Hall effect and the first term represents an effect dependent on the component of magnetization vector in the x-y plane.

When the magnetization vector lies in the plane of the sample, the planar Hall field c_y is written as

$$c_y = \frac{E_y}{j} = (\rho_{\|s}-\rho_{\perp s})\sin\phi\cos\phi \tag{2}$$

where ϕ is the angle, the magnetization vector makes with y-axis.

A bulk ferromagnet may not have its magnetization vector in the plane of the sample. So the planar Hall effect studies made on the plane of the sample

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may have some contribution from the Hall effect also. If we assume the magnetization vector making an angle θ with x-y plane, then we get the planar Hall field as

$$e_y = \frac{E_y}{j} = (\rho_{\parallel s}-\rho_{\perp s}) \sin\phi \cos\phi + \rho_{xs} \sin\theta \qquad \ldots \quad (3)$$

where $\rho_{\parallel s}$ and $\rho_{\perp s}$ in eq. (3) denote the saturation resistivities parallel and perpendicular to the direction of component of magnetization vector in the plane of the sample and ϕ the angle, the component makes with y-axis.

Hence, in the present investigation, measurements of planar Hall effect, longitudinal and transverse magneto-resistances were made on polycrystalline nickel and nickel-copper alloys from 100°K to the respective Curie points $\Delta\rho_s$ ($= \rho_{\parallel s}-\rho_{\perp s}$) computed from the magneto-resistance measurements were compared with the planar Hall field to locate the position of magnetization vector Furthermore, we have discussed the temperature dependence of these parameters on the basis of different theoretical models and have suggested a possible origin to explain these effects

2 Experimental

Spectrographically pure nickel and nickel-copper alloys of concentrations 90·62, 81·23, 71·68 and 61·87 atomic per cent nickel procured from Johnson and Mathey were used in these experiments. All the samples were annealed at 850°C for 24 hours in a vacuum furnace After annealing, the samples were cleaned thoroughly with aqua-regia and mounted on the sample holder which was constructed in such a manner that the plane of the sample could be placed along the magnetic field and the angle between the field and the current direction was varied by rotating the sample holder with respect to the magnetic field The planar Hall voltage and magneto-resistance voltages for different setting positions of the sample was measured using a d.c. potentiometric technique used earlier in this laboratory for measuring ordinary Hall voltage in metals (Dutta Roy *et al* 1969). For low temperature measurement the sample holder was placed in an evacuated glass cylinder which in turn was placed inside a dewar containing liquid air The whole system was within the pole-pieces of an electromagnet. The temperature of the sample was controlled within ±1°K by means of a heater element placed very near the sample The temperature was measured using a copper-constantan thermocouple. High temperature arrangements were same except that there was no liquid air in the dewar.

While measuring the planar Hall voltage, usual Hall e.m.f may come up from the fact that the sample plane may not be parallel to the applied magnetic field. This was eliminated by the field reversal technique. The magneto-resistance effect due to the misalignment of the probes was eliminated by measuring the values of the planar Hall voltage at $\phi = +\pi/4$ and $-\pi/4$ The mean of the four sets were taken. The thermomagnetic Etthinghausen effect, which is present in the measurement of ordinary Hall effect does not affect the measurement of planar Hall voltage (Ky 1966). The voltages corresponding to longitudinal and transverse magneto-resistances were measured at $\phi = 0$ and $\pi/2$ respectively.

Results and Discussion

Figure 1 shows the angular dependence of planar Hall field at room temperature. The sinusoidal variation is consistent with the data of Ky (1966). The spontaneous values of planar Hall field, longitudinal and transverse magneto-resistances are obtained by extrapolating the corresponding high field readings to $H = 0$ assuming a quadratic field dependence (Ky 1965) The values thus obtained are plotted as a function of composition at room temperature which are displayed in figures 2(a), (b) and (c) Figure 2(d) and (e) represent $\Delta\rho_s/\rho$ of the present investigation as well as that of Smit (1951) The agreement of the present dara with that of Smith is fairly good.

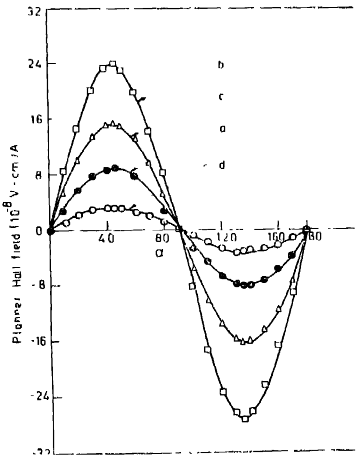

Fig. 1. The angular dependence of planar Hall fields of (a) Ni, (b) 90·62, (c) 81·23, (d) 71·68 atomic per cent nickel alloy.

It is clearly seen from figure 2 that all the four parameters pass through a maximum around 90·62 atomic per cent nickel. A similar maximum was observed in the spontaneous Hall field in our laboratory earlier (Subramayam 1968) around the same concentration suggesting that the origin for all these effects might be same.

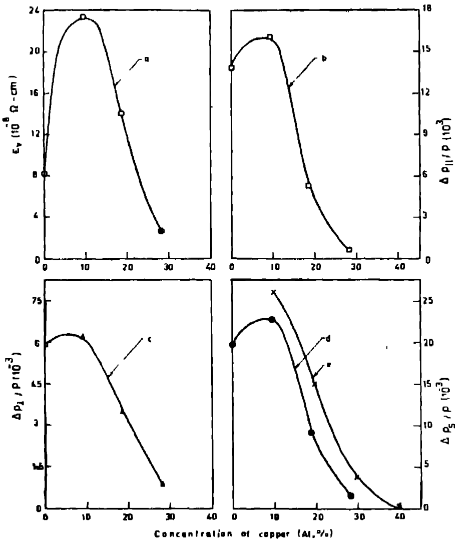

Fig. 2. Compositional dependence of (a) Planar Hall field, (b) longitudinal magneto-resistance, (c) transverse magneto-resistance, (d) magneto-resistance anisotropy and (e) the data of Smit (1951) at room temperature.

Ni-Fe and Ni-Co system have also been found to possess a maximum of magneto-resistance anisotropy, planar Hall effect and Hall effect by other research workers (Snoek *et al* 1949, Van Elst 1959, Ky 1968). They suggested that the position of the maximum should be associated with any of the following effects . (1) The magnetization corresponding to one Bohr magneton, (2) the zero magnetostriction, (3) large initial and maximum permeability, (4) the zero K_1, (5) the change in the sign of Hall coefficient around that temperature and so on. But none of the above results are found around 90·62 at per cent Ni concentration at which the maximum occurs. However, following Berger (1961), Ky (1968) attributed the maximum to the overlapping to two *d* sub-bands near the Fermi surface. He has shown for Ni-Fe alloys, considering the scattering of impurities and phonons, that the planar Hall field is proportional to $(1/\Delta)^4$ where Δ is average distance between *d* sub-bands in the spectrum of electron system Hence, if the impurity scattering model is in a position to describe the experimental results over the wide temperature range for all the alloys studied, then it may be concluded that the overlapping of d sub-bands play a prominent role in the position of maximum.

Figure 3 displays planar Hall field as well as magneto-resistance anisotropy as a function of temperature for all the alloys. It is found that even though the variation of ϵ_y and $\frac{1}{2}\Delta\rho_s$ are similar throughout the temperature region, their absolute values do not coincide suggesting that the magnetization vector may not lie in the plane of the sample. Hence from eq (3), an attempt is made to calculate θ, the angle the magnetization vector makes with the plane of the sample The values of Hall resistivity are taken from the thesis of Subramanyam (1968) who measured the spontaneous Hall resistivity as a function of Curie temperature from 300°K to the respective Curie points for the same alloy system. It is found that θ remains almost constant for nickel and its two high concentration alloys till a particular temperature which is very close to the temperature at which R_s passes through a maximum Above that temperature, θ decreases rapidly and goes towards zero as Curie temperature is reached The variation

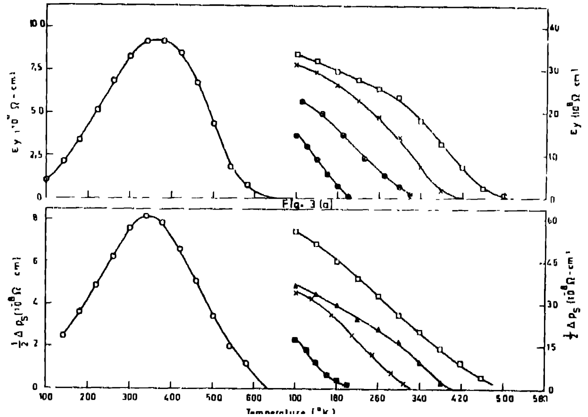

Fig 3 The temperature variation of (a) planar Hall field and (b) $\frac{1}{2}\Delta\rho_s$ for Ni and Ni-Cu alloys O, O Ni, □, □, 90·62, ×, ▲—81·23, ●, × – 71·68 and ●, ■ – 61·87 atomic percent nickel alloy.

of θ with temperature is shown in figure 4 for nickel and its two alloys The calculation of θ for temperature below 300°K was not possible due to lack of Hall resistivity data in that region

It can be seen from figure 3, ϵ_y as well as $\Delta\rho_s$ pass through a maximum around 360°K for nickel while other alloys do not exhibit a maximum Ky (1968) calculated the value theoretically to be 403°K taking into account the impurity and phonon scattering The theoretical value seems to be a little high compared to our experimental results.

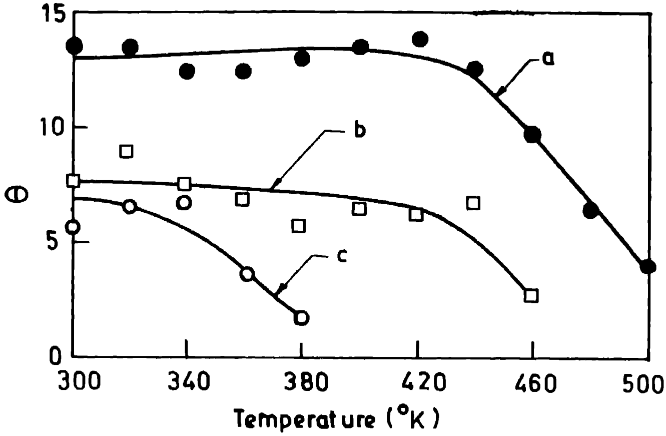

Fig 4 The temperature dependence of angle θ (the magnetization vector makes with the plane of the sample) of (a) Ni, (b) 90 62 and (c) 81 23 atomic per cent nickel alloy

It is of interest to compare the present results with that of Yu *et al* (1970) who has shown that for Ni, Co and Fe, P_s/M_s^2 (where P_s, the planar Hall coefficient, is defined as $2\epsilon_y/M_s^2$) and the spontaneous Hall coefficient R_s behave similarly in the temperature range 300°K to the respective Curie points As the compositional variation of ϵ_y and $\Delta\rho_s$ suggest the impurity scattering and phonon scattering to be responsible for these effects, an attempt is made to test the linearity between $P_s/\rho M_s^2$ and ρ as R_s is shown to obey a relationship of the type,

$$R_s = A\rho + B\rho^2 \tag{4}$$

by Cheremushkina *et al* (1966) by taking into account impurity and phonon scattering. Values of saturation magnetization $M_s(T)$ for nickel and its alloys have been taken from 0°K values of Ahren *et al* (1958) and from the Universal Curve $M_s(T)/M_s(0)$ as a function of T/T_0 reported by Bozorth (1951). Figure 5 clearly shows that the Curve is not linear for any of the alloys including nickel indicating that the similarity between P_s/M_s^2 and R_s may not exist.

However, Ky (1966) has shown theoretically that in the case of scattering of carriers by impurities and phonon, the planar Hall effect is given by the expression

$$\epsilon_y = P_s M_s^2 = C\rho_{iph}(M_s(T)/M_s(0))^2 \quad \ldots \quad (5)$$

where C is a constant for a given metal which depends on the Fermi energy E_F, the energy representing the intrinsic spin-orbit interaction, E^{s-0} and Δ, the average distance between the two d sub-bands ρ_{iph} is the resistivity due to impurity and phonon scattering, $M_s(T)$, the magnetization at temperature T and $M_s(0)$ at 0°K From eq (5), it is expected that P_s/ρ_{iph} should be a constant independent of temperature Hence P_s/ρ_{iph} is plotted as a function of tempera-

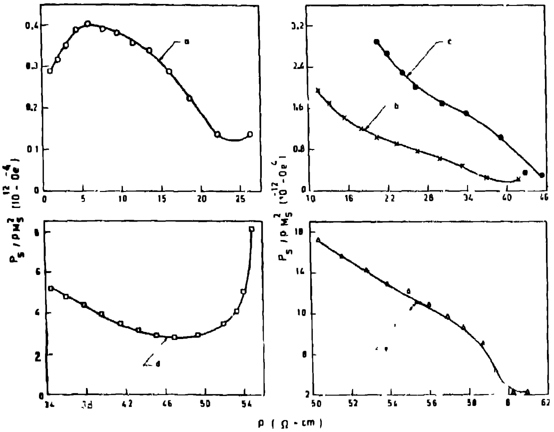

Fig 5 Dependence of $P_s/\rho M_s^2$ on ρ for (a) Ni (b) 90 62, (c) 81 23, (d) 71 68 and (e) 61·87 atomic per cent nickel alloy.

ture in figure 6 It shows that P_s/ρ_{iph} varies linearly with temperature for all the alloys through the temperature region while for nickel, it can be approximated

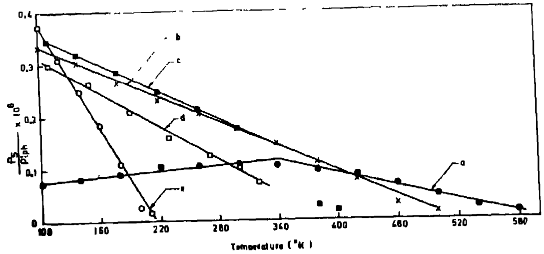

Fig. 6. Temperature variation of P_s/ρ_{iph} for (a) Ni, (b) 90 62, (c) 81 23, (d) 71·68 and (e) 61 87 atomic per cent nickel alloy.

to two straight lines As it is known that ρ_{tph} varies linearly with temperature, P_s/ρ_{tph} should obey a relationship of the type

$$P_s = a\rho_{tph} + b\rho^2_{tph} \tag{6}$$

which is true as shown in figure 7 Eq. (6) is similar to eq. (4) excepting that ρ is replaced by ρ_{tph}. This result indicates that P_s and R_s behave similarly and not P_s/M_s^2 and R_s as shown by Yu *et al* (1970).

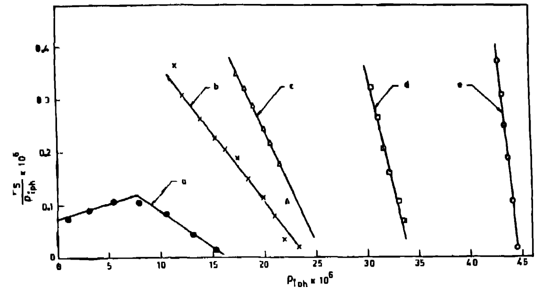

Fig 7. Dependence of P_s/ρ_{tph} on ρ_{tph} for (a) Ni, (b) 90·62, (c) 81 23, (d) 71 68 and (e) 61·87 atomic per cent nickel alloy.

It is also interesting to note that the constant b obeys a relationship of the form $-\alpha\rho^{-\beta C}$ where α and β are constants and C is the atomic per cent nickel in the sample The value of b for nickel which obeys the above relationship is observed to belong to high temperature side probably suggesting that a maximum might exist for the alloys as well, as we go towards still lower temperatures.

The first term in eq. (6) is important in the low temperature region whereas the second term contributes significantly at high temperatures where phonon scattering is very prominent. Although Ky (1966) has justified his calculation to include the scattering of electrons by phonons, he gets only a linear relationship of P_s with ρ_{tph} by neglecting higher order terms in the scattering potential. Probably the second order term neglected by him is needed to get higher order terms in ρ_{tph} This suggestion is supported by the calculation of Irkhin *et al* (1962) who found the extraordinary Hall coefficient R_s to be proportional to the square of the electrical resistivity by considering the higher order terms in the expansion of scattering potential. The discripancy in the position of maximum obtained by Ky (1968) and the present results may be probably attributed to the omission of higher order term in Ky's calculation.

4. Conclusion

It is evident from the measurements of planar Hall effect and magnetoresistances that magnetization vector of the samples measured do not lie in the plane of the sample. The maxima observed at room temperature around 90·62 at%Ni alloy is attributed to the overlapping of d-sub-bands near the Fermi surface. It is shown that similarity exists in the behaviour of P_s and R_s. Finally it is concluded that the scattering of the carriers by impurities and phonons, taking into account the higher order terms also in the scattering potential, will be in a position to explain the present experimental results.

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